Abstract. Emission of surface water on wood should be controlled because moisture movement on the wood surface initiates changes in its morphological, physical, chemical, and biological properties. In this study, surface moisture content (SMC) of yellow poplar (Liriodendron tulipifera L.) wood was measured by a near-infrared spectroscopy (NIRS) technique, nondestructively and continuously, during unsteady-state desorption conditions. With these SMC data, surface emission coefficients (SECs) were determined continuously while the wood was being dried. These experimentally determined coefficients were compared with values that were converted from the theoretically determined mass transfer coefficients. The conversion method, which was developed to facilitate a comparison among the mass transfer coefficients, indicated that the boundary layer theory was useful in evaluating the degree of external moisture resistance while the wood dried. Also, the NIRS technique can be used for determining SEC at each specific point of wood, experimentally, in real time.

Keywords: Surface emission coefficient, surface moisture content, Hart’s method, boundary layer theory, near-infrared spectroscopy.
INTRODUCTION

Moisture movement rate inside wood is generally expressed in terms of diffusion coefficient. When moisture in wood moves from one point to another and if the coefficient is assumed to be constant and the outside surfaces of specimens are assumed to immediately come to equilibrium with uniform temperature and moisture content or pressure of the surrounding air, then it is possible to obtain the general solution to Fick’s diffusion law through the separation of variables method. This solution has been widely used for approximating the moisture profile change in wood well, especially in thick wood (Choong 1963; Comstock 1963; McNamara and Hart 1971; Siau 1995; Yeo and Smith 2005).

The movement rate from the surface to the outside air is explained using the convection coefficient or the surface emission coefficient (SEC), which many studies have used to assess moisture movement on wood (Avramidis and Siau 1987).

In general, the coefficient of mass transfer is proportional to the difference in the moisture concentration or water vapor pressure (WVP) in the air or moisture content and water evaporation rates. This value depends on the properties of the ambient airflow (temperature and velocity) and diffusion capability of a moving substance (moisture) into the ambient airflow. SEC is also a type of coefficient of mass transfer, ie a proportional coefficient pertaining to the differences between the surface moisture content (SMC) and equilibrium moisture content (EMC) and the absorption or desorption rates. Because this value is based on moisture content, it is influenced mainly by the moisture adsorption performance of the adsorbent substance as well as by ambient air properties.

The convective mass transfer coefficient that is determined by boundary layer theory, which is well established and used in engineering fields, is based on moisture concentration in a certain volume of air, whereas the convective mass transfer coefficient determination method as presented by Hart (1977) is based on the potential of WVP (Yeo et al 2008). According to Hart, the maximum flux of moisture evaporating from the surface of wood into the ambient air can be controlled by the difference between saturated vapor pressure of water on the wood surface and WVP in the ambient air.

The two methods, boundary layer theory and Hart method, determine a constant coefficient that is calculated by a certain temperature and velocity of air on only wet wood surfaces. To determine the emission rate of water on the surface of wood in the hygroscopic range, an appropriate conversion among coefficients based on different driving forces is needed.

This study suggested methods to convert the convection coefficient determined by boundary layer theory and Hart method into SEC based on SMC. Then, results from both conversion methods were compared with SEC determined by measuring the SMC using near-infrared spectroscopy (NIRS).

If the experimentally determined SEC is similar to the converted coefficients, then moisture emission from the wood surface, previously unproven, can be considered to be theoretically proven. In other words, if the temperature and speed of the ambient air are known, the convection coefficient with the boundary layer theory can be calculated. Then, using this value and the absorption/desorption curve (the relationship between RH and EMC) of wood or any moisture-absorbent material, SEC can be calculated according to SMC. SEC can also be used in real-time evaluations, in future predictions, and for control of the moisture evaporation rate of a wood surface in unsteady-state (under a real process) conditions and tasks, which until now had been difficult.

In this study, the convection coefficients determined by boundary layer theory and Hart method were converted into SEC with the proposed convection coefficient conversion equation. Those were compared with the SEC determined using SMC, which was measured by NIRS. Furthermore, this study intends to prove that it is possible to convert the convection coefficient as developed by a theoretical
analysis of the temperature slope and speed of the ambient airflow by revealing their degree of similarity.

**MATERIALS AND METHODS**

To evaluate SEC, a 35-yr-old yellow poplar (Liriodendron tulipifera) tree with a diameter of 400 mm was cut down from the Gangjin forest in Korea. The initial moisture content recorded from the wood taken from the tree was 80%. Logs were cut into boards of 50 mm thick and were prepared in dimensions of 50 × 50 × 5 mm (longitudinal × tangential × radial). Each specimen was soaked in distilled water. After soaking, moisture content of the specimens was between 129 and 180%. In total, 12 specimens were prepared, and 3 specimens were used for each drying condition.

The specimens were dried under four different drying conditions (Table 1) using a humidity chamber (maintained at 25, 50, 75, and 90°C). The velocity of air inside the device was 2.0 m/s. The near-infrared (NIR) reflectance of the radial surface of the specimen was acquired by an NIR spectrometer (NIRQUEST 256-2.5; Ocean Optics, Dunedin, FL) to measure the SMC of the specimens during drying. The spectra acquisitions of specimens were taken indoors by inserting an optical probe into the chamber to decrease the possibility of any error that may have occurred when the specimen was taken outside. Prediction of SMC using NIRS was performed by the regression model developed in a previous study (Eom 2011).

SEC (S = h\textsubscript{H2O,wood}) based on moisture content of wood was determined by Eq 1, whereas the SMC of wood was measured by the NIR spectra in an unsteady state. However, the EMC of wood was measured when it was stabilized with the surrounding air.

\[
\frac{dw}{dt} = S \cdot A \left( \frac{\text{SMC}}{100} \cdot G\text{SMC} - \frac{\text{EMC}}{100} \cdot G\text{EMC} \right)
\]

where \(S(= h_{\text{H2O,wood}})\) = surface emission coefficient (m/s), \(w = \) evaporated water weight (g), \(t = \) time (s), SMC = surface moisture content (%), EMC = equilibrium moisture content (%), \(A = \) surface area (m\(^2\)), and \(G\text{SMC}, G\text{EMC} = \) specific gravities of wood based on the oven-dry weight and volumes at SMC and EMC.

The convective mass transfer coefficient caused by the difference in WVP can be determined experimentally using Hart’s method. According to Hart (1977), when the maximum moisture flux from a wet wood surface is in its initial drying stage, WVP is assumed to be saturated at the wet-bulb temperature. The WVP in air is a constant vapor pressure as determined by dry-bulb and RH conditions. With WVP and maximum moisture flux, the value of \(h_p\text{,Hart}\) was determined using Eq 2:

\[
h_p\text{,Hart} = \frac{J}{(p_{o\text{-wet}} - p_e)}
\]

where \(J = \) moisture flux (kg/s m\(^2\)), \(p_{o\text{-wet}} = \) saturated WVP at the wet-bulb temperature (Pa), and \(p_e = \) WVP in ambient air at the dry-bulb temperature. This vapor pressure was determined by percentage RH multiplied by saturated WVP at the dry-bulb temperature.

However, if we consider the change in surface moisture in an unsteady state, when the partial vapor pressure of the air adjacent to the surface is not the saturated WVP at the wet-bulb temperature, we can obtain the following equation by replacing \(p_{o\text{-wet}}\) with \(p_s\) as the convection coefficient calculated with WVP.

\[
h_p = \frac{J}{(p_s - p_e)}
\]

where \(h_p = \) convective mass transfer coefficient based on the potential of the WVP (kg/m\(^2\cdot\)s·Pa),
$J = \text{moisture flux from the surface to the air (kg/m}^2\text{s)}, \ p_s = \text{WVP in the air adjacent to the wood surface (Pa)}, \ p_e = \text{WVP in ambient air at the dry-bulb temperature (Pa)}.$

In this case, if SMC can be measured in real time, then we can determine the RH of the air adjacent to the surface and, thus, define the partial vapor pressure of the air as follows (Yeo 2001):

$$p_s = p_{0,\text{wet}} - \left(\frac{p_{0,\text{wet}} - p_e}{100 - RH_s}\right) \cdot (100 - RH_s) = \left(\frac{p_{0,\text{wet}} - p_{0,\text{dry}} \cdot \left(\frac{RH_s}{100}\right)}{100 - RH_s}\right) \cdot (100 - RH_s) \quad (4)$$

where $p_{0,\text{wet}}$ = saturated WVP at the wet-bulb temperature (Pa), $p_{0,\text{dry}}$ = saturated WVP at the dry-bulb temperature (Pa), $RH_s = \text{RH of ambient air (\%)},$ and $RH = \text{RH of air adjacent to the wood surface (\%)}. $

A conversion equation (Eq 5) can be formulated by considering the differences in the wood moisture content levels and the differences in the WVP as the driving force. With this conversion equation, SEC according to the partial vapor pressure of the air adjacent to the surface is determined.

$$S = \frac{h_{H2O,\text{wood}}}{h_{H2O,\text{air}}} = h_p \cdot \left(\frac{(p_s - p_e)}{(C_{s,\text{wood}} - C_{c,\text{wood}})}\right) = h_p \cdot \left(\frac{G_{\text{SMC}} \cdot \rho_w \cdot \left(\frac{\text{SMC}_{\text{100}} - \text{GEMC}}{\text{100}}\right)}{\rho_s - \rho_e}\right) \cdot \left(\frac{\text{G}_{\text{SMC}} \cdot \text{G}_{\text{EMC}} \cdot \rho_w \cdot \left(\frac{\text{SMC}_{\text{100}} - \text{GEMC}}{\text{100}}\right)}{\rho_s - \rho_e}\right) \quad (5)$$

where $S = \text{surface emission coefficient (m/s)}, \ C_{s,\text{wood}} = \text{moisture concentration in the wood at the surface (kg/m}^3\text{)}, \ C_{c,\text{wood}} = \text{moisture concentration in the wood in equilibrium with air (kg/m}^3\text{)}, \rho_w = \text{density of water (kg/m}^3\text{)}, \text{SMC, EMC = surface and equilibrium moisture contents (\%), and G_{SMC, GEMC = specific gravities of wood based on oven-dry weight and volumes at SMC and EMC.}}$

The convective mass transfer coefficient ($h_{H2O,\text{air}}$), according to the moisture concentration of air, can be determined using the boundary layer theory (Eq 6).

$$h_{H2O,\text{air}} = \frac{0.66D_{H2O,\text{air}}Re^{0.5}Sc^{1/3}}{L_s} \quad \text{for laminar flow} \quad (6)$$

where $h_{H2O,\text{air}} = \text{convective mass transfer coefficient averaged across the length } L_s \text{ (m/s), } D_{H2O,\text{air}} = \text{diffusion coefficient of water vapor in air (m}^2\text{s)} \text{ (Dushman's equation, cited in Siau 1995), } Re = \text{Reynolds number, } Sc = \text{Schmidt’s number, } L_s = \text{length of the surface along which convection occurs (m), } v = \text{air velocity (m/s), } \rho_s = \text{density of air (kg/m}^3\text{), and } \mu = \text{dynamic viscosity of air (Pa-s).}$

To convert the convective mass transfer coefficient ($h_{H2O,\text{air}}$) to SEC(S), converting Eq 7 was applied:

$$S = \frac{h_{H2O,\text{wood}}}{h_{H2O,\text{air}}} = \frac{(C_{s,\text{air}} - C_{c,\text{air}})}{(C_{s,\text{wood}} - C_{c,\text{wood}})} = h_{H2O,\text{air}} \cdot \left(\frac{M_{H2O}P_0}{R T_s} - \frac{M_{H2O}P_e}{R T_{dry}}\right) \cdot \left(\frac{G_{\text{SMC}} \cdot \rho_w \cdot \left(\frac{\text{SMC}_{\text{100}} - \text{GEMC}}{\text{100}}\right)}{\rho_s - \rho_e}\right) \quad (7)$$

where $C_{s,\text{wood}} = \text{moisture concentration in wood at the surface (kg/m}^3\text{)}, \ C_{c,\text{wood}} = \text{moisture concentration in wood in equilibrium with air (kg/m}^3\text{)}, \ C_{s,\text{air}} = \text{moisture concentration in ambient air (kg/m}^3\text{)}, M_{H2O} = \text{water molecular weight (18 kg/mol), } R = \text{universal gas constant, 8314 m}^3\text{ Pa/(kmol K), } T_s = \text{surface temperature (K), and } T_{dry} = \text{dry-bulb temperature (K).}$

Through this, an attempt was made to verify that SEC, converted from the convective mass transfer coefficient (as calculated with the boundary layer theory), could be used to assess the moisture movement outside and on the wood surface in an unsteady state under diverse ranges of temperature and RH.

**RESULTS AND DISCUSSION**

Figure 1 shows the SMC of the specimen measured using NIRS during drying. The decrement
rate of SMC increased with increase in temperature. The SMC of the specimen reached EMC after approximately 3 h at 75°C. It took the specimen about 8 h to reach EMC at 50°C and about 16 h at 25°C.

SMC of wood was measured by NIRS in an unsteady state, and SEC was determined from the result (Fig 2). Figures 3 and 4 illustrate the trend of the calculated SEC using Hart’s method and boundary layer theory during drying.

With the three methods, SEC of all specimens was calculated below FSP because the root mean square error prediction (RMSEP) of the regression model of SMC above FSP was greater than below FSP. Below FSP, RMSEP rapidly increased for SEC calculated by both
Hart’s method and boundary layer theory with moisture content decrement. Thus, it can be concluded that the external resistance (1/SEC) decreased with decreasing SMC during drying. The calculated SEC at 90°C was greater than those at other temperatures and was nearly constant at 25 and 50°C. Generally, wood drying rate is faster at higher temperatures (Figs 3 and 4). As the temperature around the wood increases, it gives heat energy to the moisture inside and outside the wood, increasing the moisture activity and moisture evaporation. Specimens with the same moisture contents will have higher SEC at higher temperatures. This trend appears similar in SEC determined by all three methods.

Figure 2 was plotted with SEC from Eq 1 substituted by SMC prediction results of NIRS. Thus, Fig 2 is almost similar to Figs 3 and 4.
SMC measurement was essential for determining SEC in Eq 1; however, mathematical analysis for SEC was carried out by applying Hart’s method and boundary layer theory because SMC was difficult to measure. SMC measurement using NIRS simplified the calculation of SEC except for the consideration of major factors of drying rate, such as temperature, humidity, and air velocity. SEC changes according to the vapor pressure around the wood surface; it increases as the temperature increases and moisture content decreases.

Figure 5 shows SEC at different temperatures as determined by the three methods. SEC determined using SMC measured by NIRS was similar to those converted from mass transfer coefficients, which were determined by Hart’s method and by the boundary layer theory. The results show that the conversion method, which was developed to facilitate comparison among the mass transfer coefficients, indicated that the boundary layer theory was useful in evaluating the degree of external moisture resistance while the wood dried, and the theoretically determined SEC was verified experimentally. Also, the results show that the NIRS technique can be used for determining SEC at each specific point of wood, experimentally, in real time.

CONCLUSIONS

In this study, SMC of yellow poplar (*Liriodendron tulipifera* L.) wood was measured by an NIRS technique, nondestructively and continuously, during unsteady-state desorption conditions. A reliable pattern of SMC change was monitored by the NIRS technique during actual drying.

With these surface moisture data, SEC was determined continuously while the wood was being dried. These experimentally determined SECs were similar to SECs that were converted from...
convective mass transfer coefficients determined by Hart’s method and by the boundary layer theory.

The conversion method, which was developed to facilitate comparison among the mass transfer coefficients, indicates that the boundary layer theory, which determines a constant coefficient varied by a certain temperature and velocity of air on only the wet wood surface, is useful in evaluating the emission rate of water on the surface of wood in the hygroscopic range. The results showed that the NIRS technique can be used for determining SEC at each specific point of wood, experimentally, in real time.

The analytical techniques used in this study will help in precisely controlling moisture transfer in various processes of moisture-absorbent substances and also provide a theoretical foundation for examining moisture transfer phenomena at the microscale.

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